Basic principles of Particle Identification (PID)

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Introduction

✓Particle Identification (PID) is a crucial aspect of most High Energy Physics (HEP) experiments
The detectors which are used depend on the physics that is under study

✓In a typical experiment beams collide within the detectors (or a single beam collides with a fixed target)
We wish to reconstruct as fully as possible the resulting events, in which many particles emerge from the interaction point

✓**Tracking** detectors detect charged particles, and in conjunction with a magnetic field, measure the sign of the charge and the momentum of the particle

✓**Calorimeters** detect neutral particles, measure the energy of particles, and determine whether they have electromagnetic or hadronic interactions

✓What other information do we need?

Elementary particles

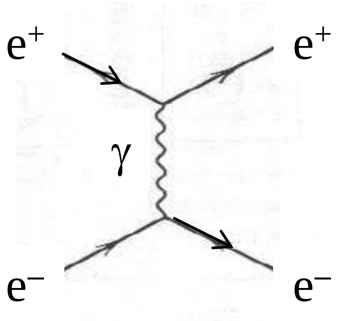
✓The fundamental elementary particles of the Standard Model are the following:

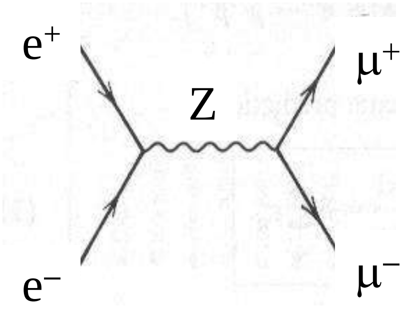
Type	**Name**			**Charge**	**Spin**
Generation	1st	2nd	3rd		
Leptons	**e** ν_e	**μ** ν_μ	**τ** ν_τ	1 0	1/2 1/2
Quarks	**u** **d**	**c** **s**	**t** **b**	2/3 1/3	1/2 1/2
Force	Strong	EM	Weak		
Gauge bosons	**g**	γ	**Z** **W**	0 1	1 1
Higgs boson	**H**			0	0

✓How can each of these be identified in the experiment?
Also need to be ready to detect particles from beyond the SM

Gauge bosons

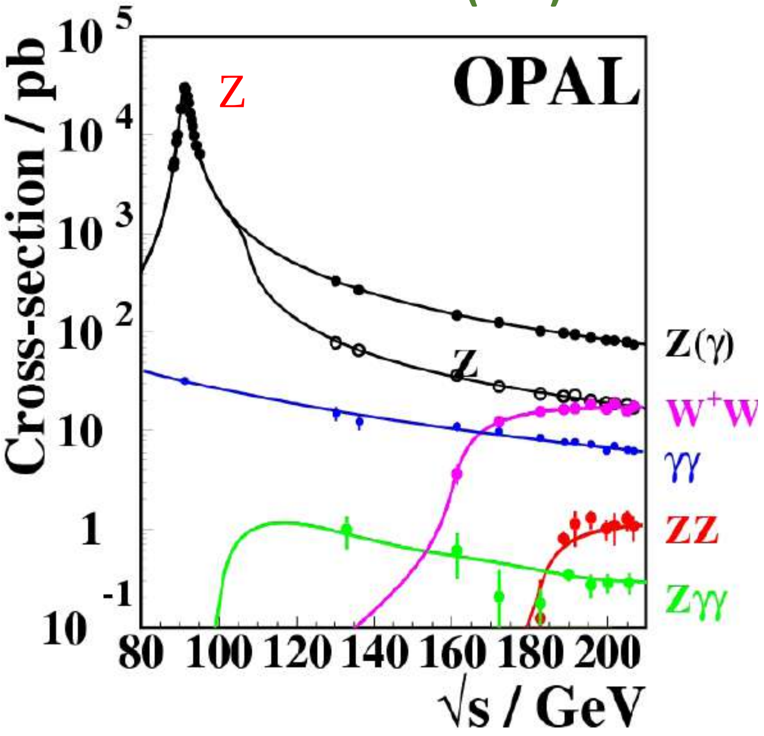
- ✓ Gauge boson play the role of (virtual) particles exchanged between fermions:





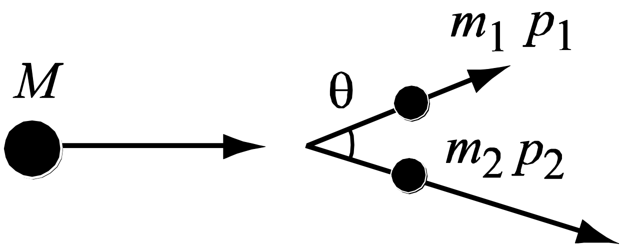
- ✓ However, real, massless photons can be produced, and seen in the experiment
- ✓ Weak vector bosons (W, Z) are massive, and therefore very short lived
- ✓ They can be seen from the variation of cross section with energy, or from their decay products

Cross section for
$e^+ e^-$ collisions (LEP)



Invariant mass

- ✓ From relativistic kinematics, the relation between energy E, momentum p, and (rest) mass m is: $E^2 = p^2 + m^2$
  (The full expression: $E^2 = p^2c^2 + m^2c^4$ but factors of c are often dropped)
- ✓ Consider a particle that decays to give two daughter particles:



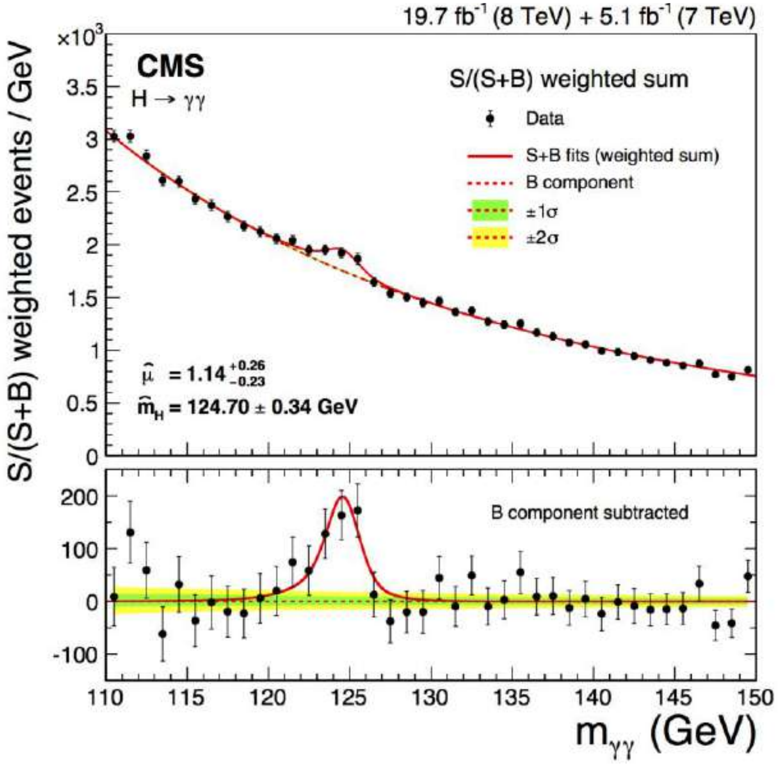
- ✓ The invariant mass of the two particles from the decay:

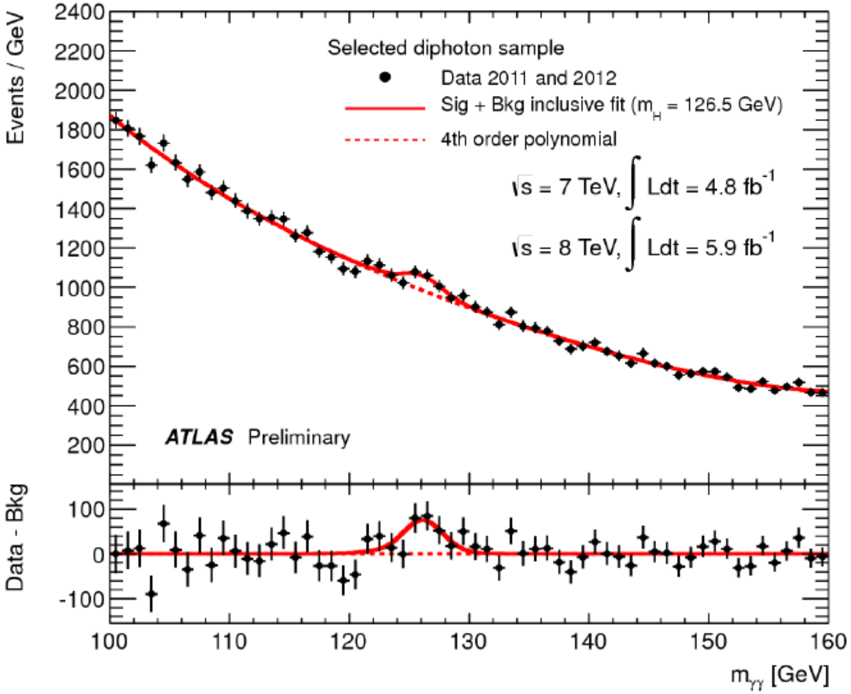
$$M^2 = m_1^2 + m_2^2 + 2\,(E_1E_2 - p_1\,p_2\cos\theta\,)$$

→ to reconstruct the mass a precise knowledge of the momentum and the angle θ of decay products is needed, from the tracking system, as well as well as their particle type, which determines their masses m_1 and m_2

Mass reconstruction

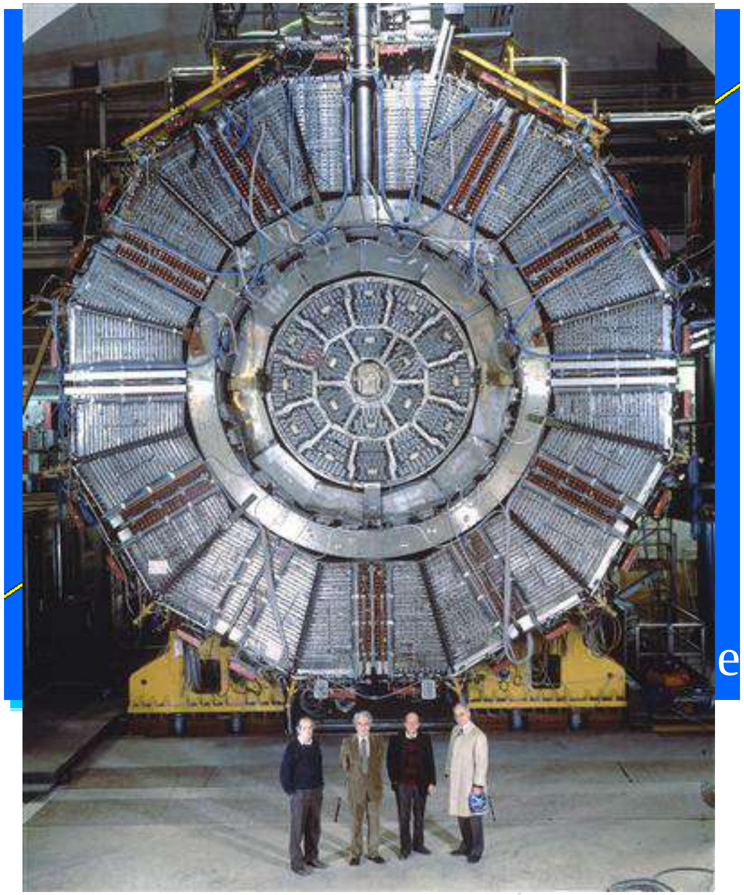
- ✓ Typical example of reconstruction of a Higgs decay: **$H \rightarrow \gamma\gamma$** reconstructed in the LHC experiments





Event display

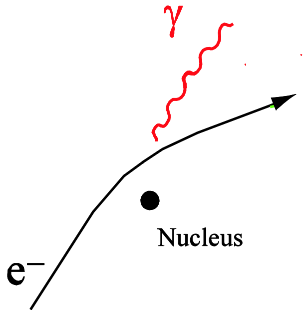
- ✓ The different particle signatures can be illustrated using events from of one of the experiments at LEP (the previous accelerator to the LHC at CERN)
- ✓ ALEPH took data from 1989–2000, studying e^+e^- collisions from LEP
- ✓ Event display is fish-eye view in the plane transverse to the beams, showing the hits in the different detectors



ALEPH

Identification techniques

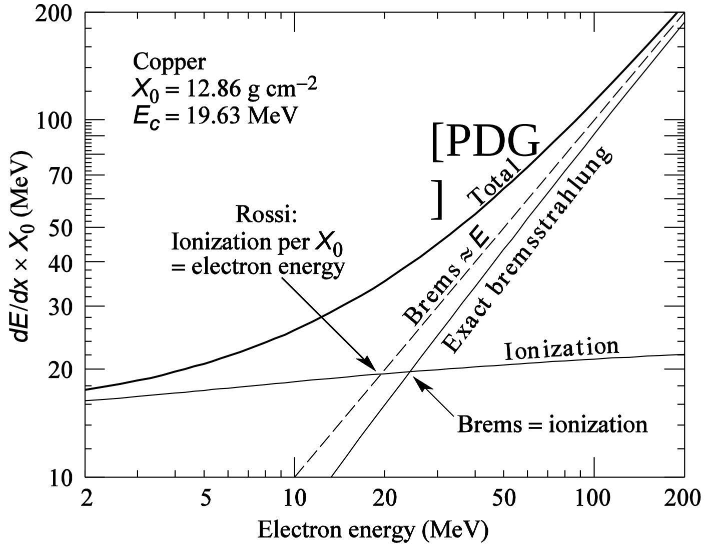
- ✓ The various elementary particles give different characteristic signatures in the separate detectors that make up the experiment
- ✓ Charged leptons leave tracks due to ionization in the tracking detectors
- ✓ Electrons are stable particles and have low mass (m_e = 0.51 MeV) They produce Bremsstrahlung radiation when passing through matter



$\Delta E \propto 1/m^2$

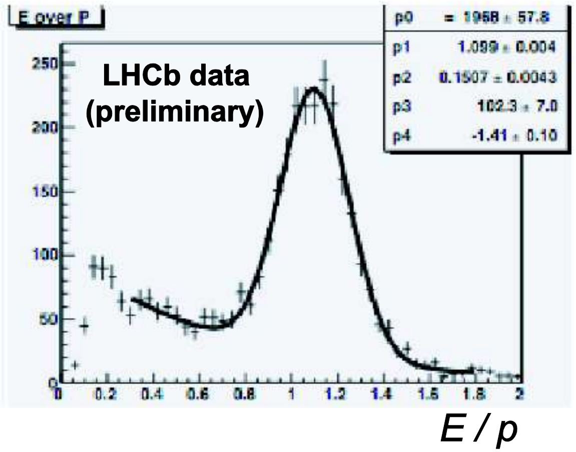
Dominates for electrons with

E > 100 MeV



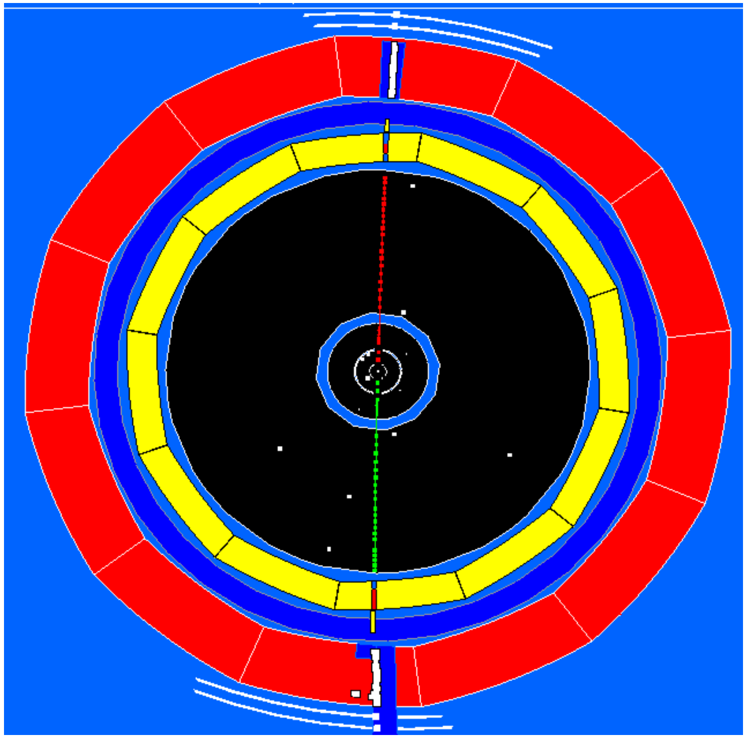
e/γ identification

- ✓ When incident on matter at high energy, photons convert to e^+e^- pairs
  Since the electrons (and positrons) produce more photons by Bremsstrahlung, a shower develops of $e^\pm$ and photons, until the energy of the incident particle has been used up
- ✓ Radiation length $\mathbf{X_0}$ = mean distance to reduce energy by **1/e**
  eg $\mathbf{X_0}$ **= 1.76 cm** for Fe, so these electromagnetic showers are compact
- ✓ Such showers are similar for electrons and photons
  Distinguished by the existence (or not) of a track associated to the shower
- ✓ For the electron, E (energy measured in EM calorimeter) and p (momentum from tracker) should be equal: **E/p = 1**
- ✓ Not the case for other charged particles



Muons

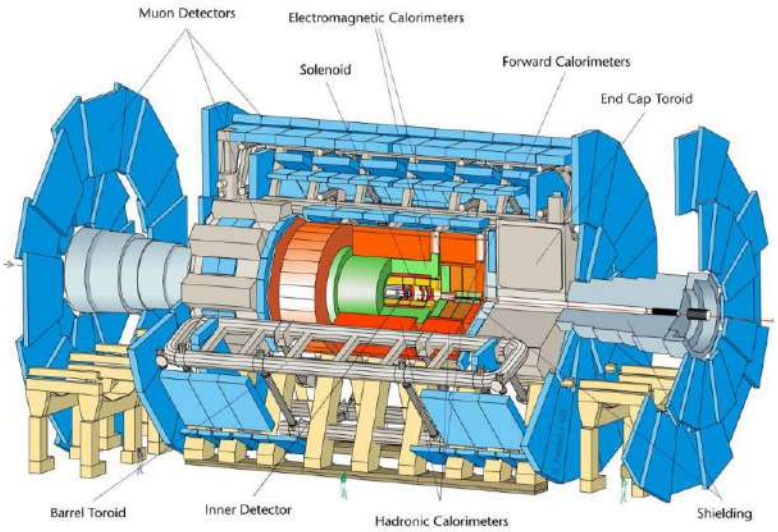
- ✓ Muons act like heavier versions of the electron, with mass 105.7 MeV
- ✓ They decay to electrons $\mu^- \to e^-\nu_e\nu_\mu$ with (proper) lifetime $\tau_\mu = 2.2\ \mu s$
- ✓ Distance they travel (on average) before decay: $d = \beta\gamma c\tau_\mu$
  where velocity $\beta = v/c$
  boost $\gamma = E/m = 1/\sqrt{(1-\beta^2)}$
- ✓ So a 10 GeV muon flies ~ 60 km before decay >> detector size
  → effectively stable
- ✓ Since mass is large, Bremsstrahlung radiation is small, and as a lepton it does not feel the strong interaction

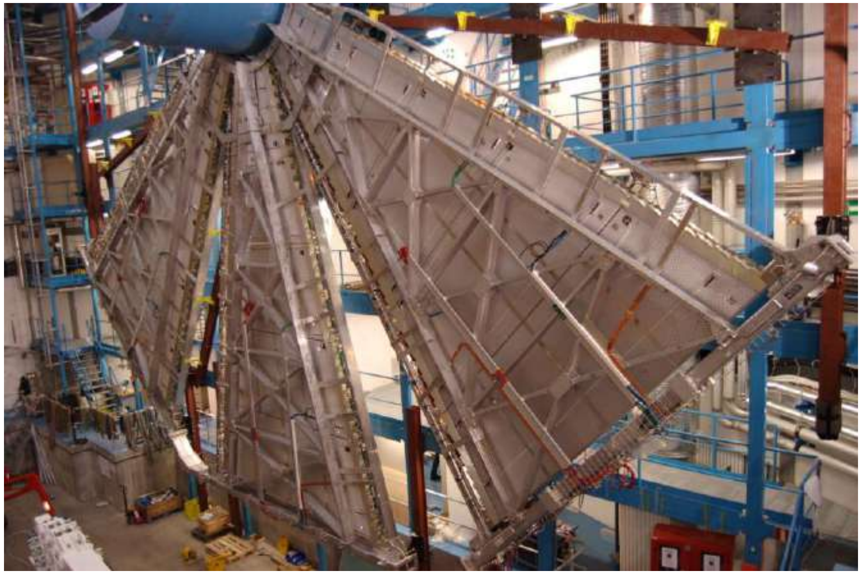


→ **most penetrating charged particle**

Muon detectors

- ✓ Since they are sited on the outside of an experiment, muon detectors tend to have very large size

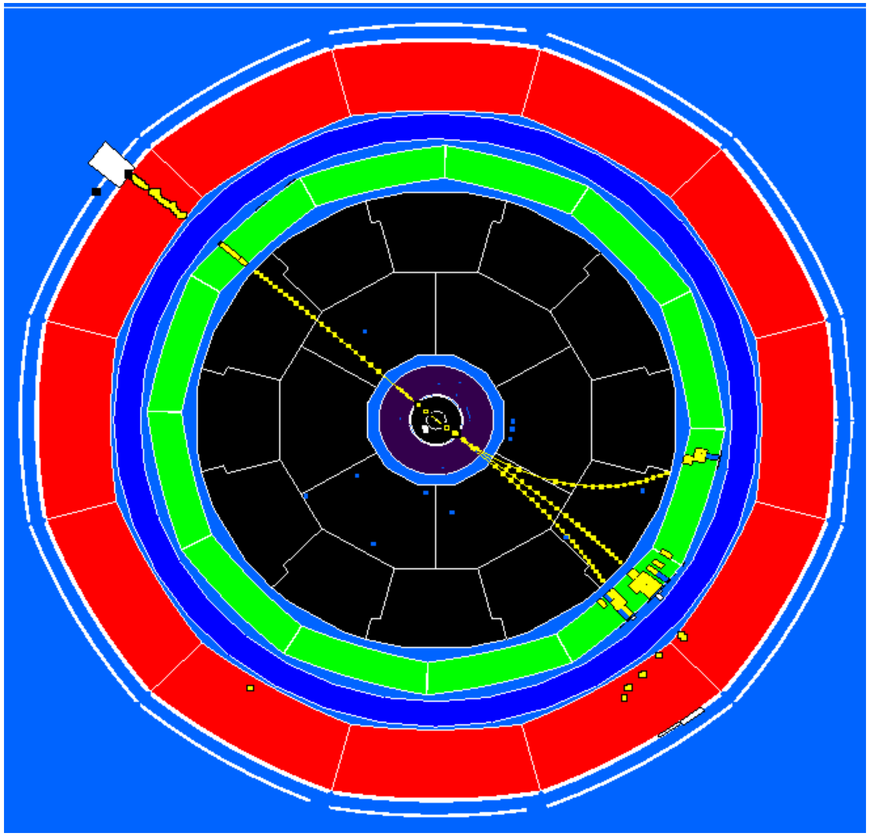




- ✓ They must be inexpensive, low granularity but precise enough for p measurement

Tau leptons

- ✓ Taus are heavier still, m_τ = 1.78 GeV
- ✓ Heavy enough that can decay to many final states: $\tau^- \rightarrow \mu^-\nu_\mu\nu_\tau$, $\pi^-\nu_\tau$, $\pi^-\pi^0\nu_\tau$, $\pi^-\pi^-\pi^+\nu_\tau$, …
- ✓ Lifetime τ_τ = **0.29 ps (ps = 10^{-12} s)** so a 10 GeV tau flies ~ 0.5 mm
- ✓ This is typically too short to be seen directly in the detectors
- ✓ Instead the decay products are seen
- ✓ Accurate vertex detectors can detect that they do not come exactly from the interaction point



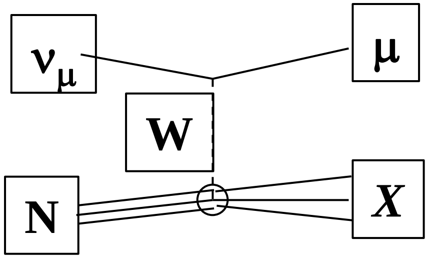
Neutrinos

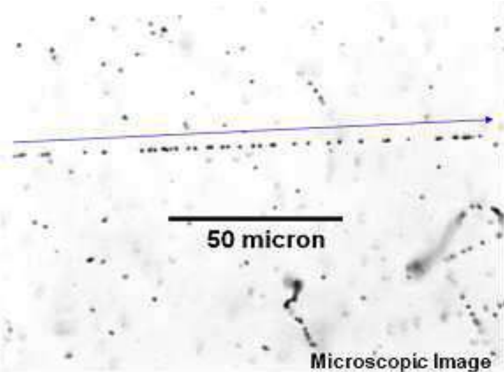
- ✓ Neutral (i.e. no track) and only weak interaction → pass through matter easily
- ✓ Interaction length **λ_{int} = A /(ρ σ N_A),** cross section **σ ~ 10^{-38} cm^2 × E [GeV]** → a 10 GeV neutrino can pass through > million km of rock
- ✓ Neutrinos are usually detected in HEP experiments through missing energy (applying E conservation to rest of the event, usually in transverse plane E_T)
- ✓ Nevertheless their interactions can be detected if you produce enough of them, and the detector is sufficiently massive

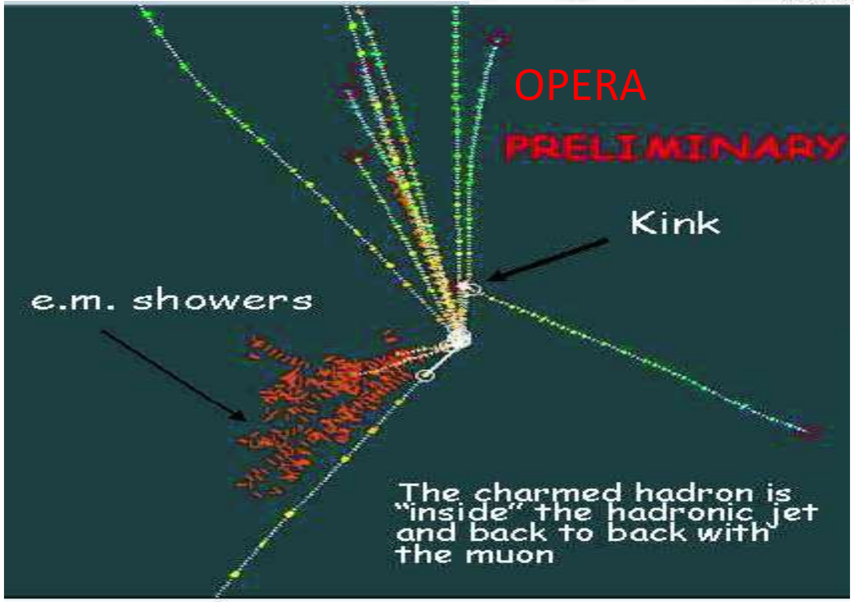
> 1 kton of instrumented target mass!

Neutrino flavours

- ✓ Can even determine the neutrino flavour (ν_e, ν_μ, ν_τ) from their charged-current interaction: $\boldsymbol{\nu_\mu\ N \rightarrow \mu^-\ X}$, etc
- ✓ OPERA searched for ν_τ created by neutrino oscillation from a ν_μ beam (sent 730 km from CERN to Italy)
- ✓ Tau decay seen as track kink in a high precision emulsion detector, interleaved with lead sheets to provide the high mass of the target







The charmed hadron is "inside" the hadronic jet and back to back with the muon

QUIZZ

Comment on the experimental techniques / detectors used to identify:

✓ Gauge bosons: W, Z, gamma

✓ Higgs boson

✓ Charged leptons:

- electrons
- muons
- tau leptons

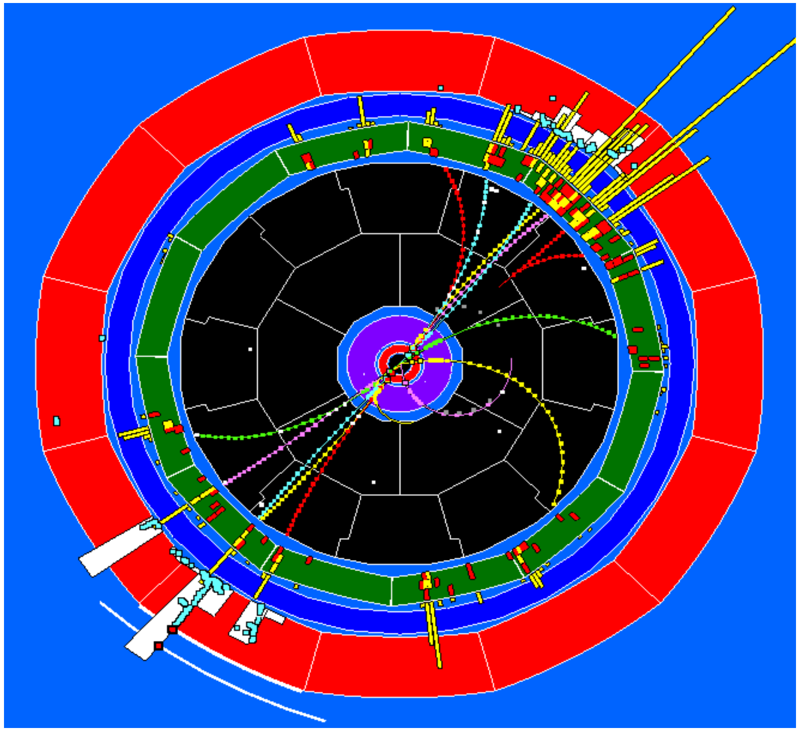
✓ Neutrinos

Quarks

- Quarks feel the strong interaction, mediated by gluons
- Not seen in the detector, due to confinement property of QCD

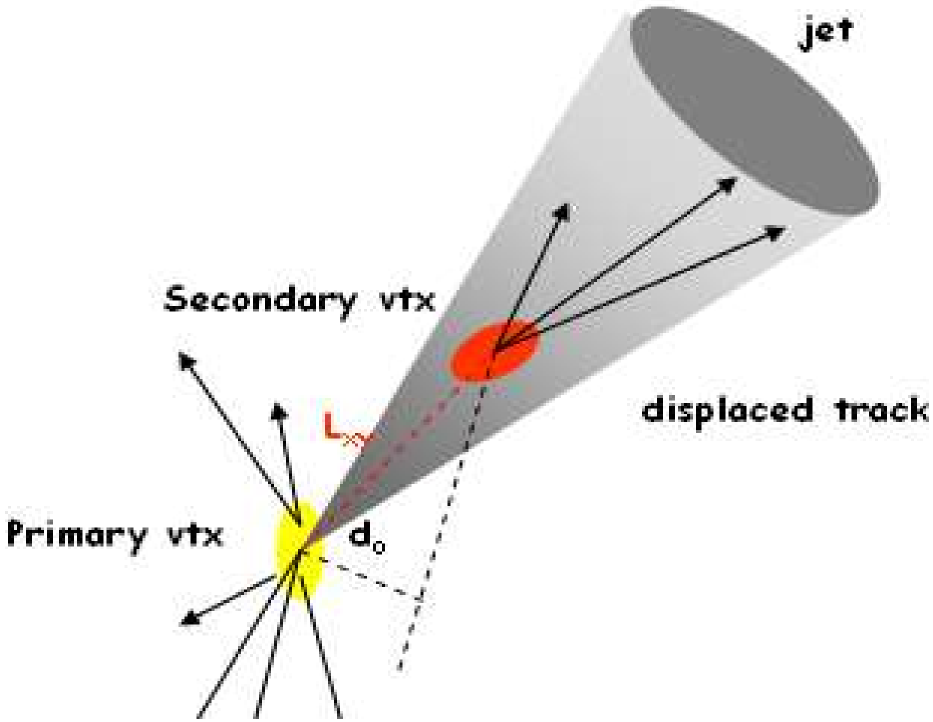
✓ Instead, they hadronize into mesons **($q\bar{q}$)** or baryons **(qqq)**

- At high energy **>> m_q**
  initial quark (or gluon) produces a **"jet"** of hadrons
- Gluon and quark jets are
  difficult to distinguish:
  gluon jets tend to be wider, and have a softer particle spectrum



Jet reconstruction

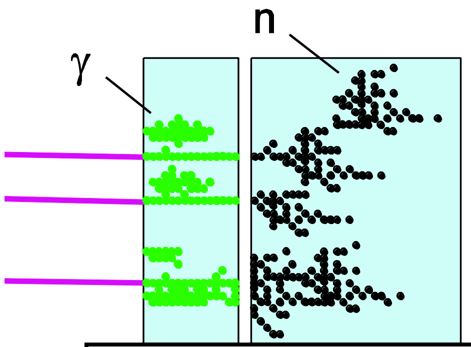
- ✓ Jets are reconstructed by summing up the particles assigned to the jet
- ✓ Typically performed using a conical cut around the direction of a “seed” particle, or by iteratively adding up pairs of particles that give the lowest invariant mass
- ✓ Different quark flavours can be separated (at least statistically) by looking for displaced tracks from b- and c-hadron decays
- ✓ The jet properties can be used to approximate the quark or gluon



Particle Flow

- ✓ In a typical jet:
  60 % of jet energy is from charged hadrons
  30 % from photons (mainly from π^0)
  10 % from neutral hadrons (n and K_L^0)
- ✓ The traditional approach to jet reconstruction:

  Measure all of jet energy in calorimeters
  → ~ 70 % of energy measured in HCAL
  Poor HCAL resolution limits jet resolution:
  $\Delta E/E \sim 60\% /\sqrt{E}$

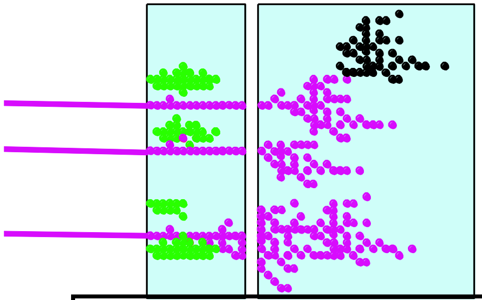


$E_{jet} = E_{ECAL} + E_{HCAL}$

- ✓ Particle Flow approach:
  Charged particles well measured in tracker
  Photons in ECAL
  Neutral hadrons (only) in HCAL

  → Only **10 %** of jet energy taken from HCAL

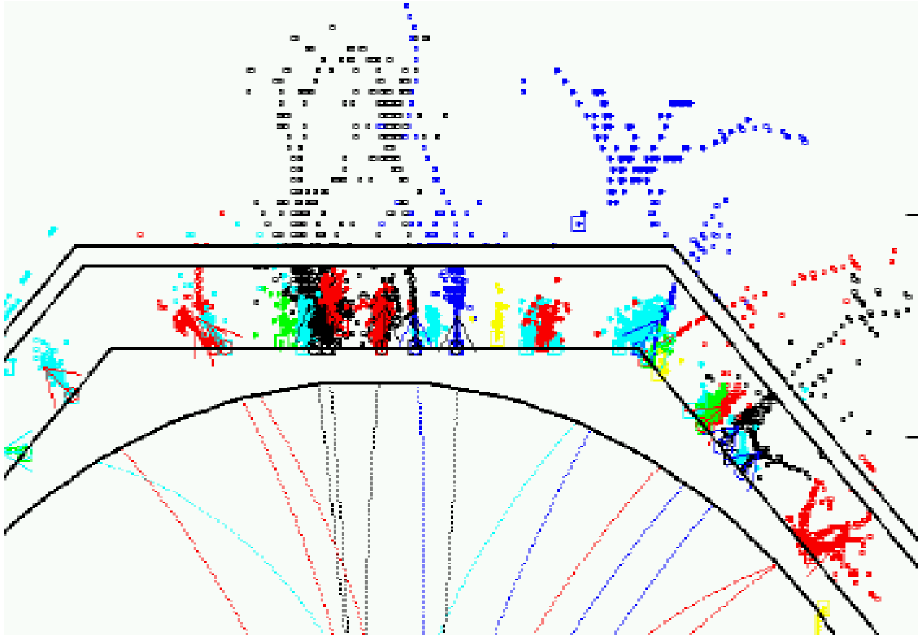
  $\Delta E/E \sim 30\% /\sqrt{E}$ may be achieved



$E_{jet} = E_{track} + E_{\gamma} + E_n$

Particle-flow calorimetry

- ✓ The main remaining contribution to the jet energy resolution comes from the confusion of contributions, from overlapping showers etc
- ✓ Most important is to have high granularity of calorimeters to help the (complicated) pattern recognition
- ✓ This is the approach being studied for detectors at the future e^+e^- linear collider **(ILC or CLIC)**



Simulated event in an ILC detector

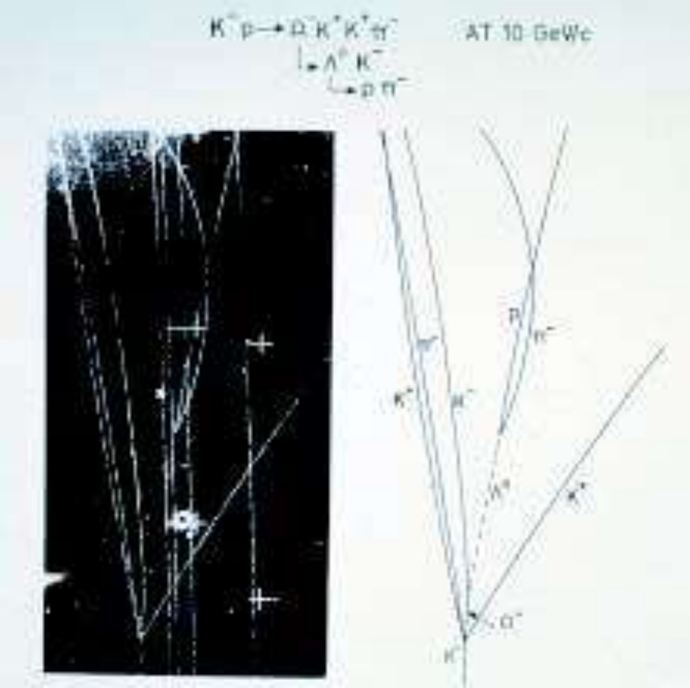
Hadrons

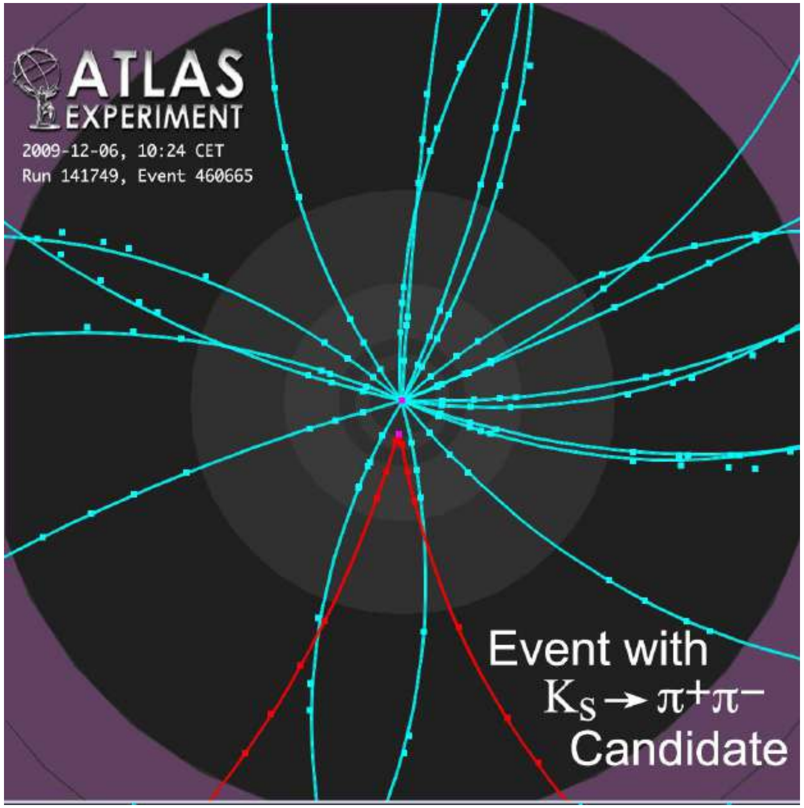
- ✓ Instead of making do with jet reconstruction, often the physics under study requires the identification of individual hadrons
- ✓ Most are unstable, and decay into a few long-lived particles:

Particle	***m* [MeV]**	**Quarks**	**Main decay**	**Lifetime**	***c*τ [cm]**
$\pi^{\pm}$	140	ud	$\mu\nu_{\mu}$	2.6×10^{-8} s	780
$K^{\pm}$	494	us	$\mu\nu_{\mu}$, $\pi\pi^{0}$	1.2×10^{-8} s	370
K_S^0	498	ds	$\pi\pi$	0.9×10^{-10} s	2.7
K_L^0	498	ds	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{34}$ years	∞
n	940	udd	$pe\nu_e$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

V^0s

- ✓ K_S^0 and Λ are collectively known as V^0s, due to their characteristic two-prong decay vertex



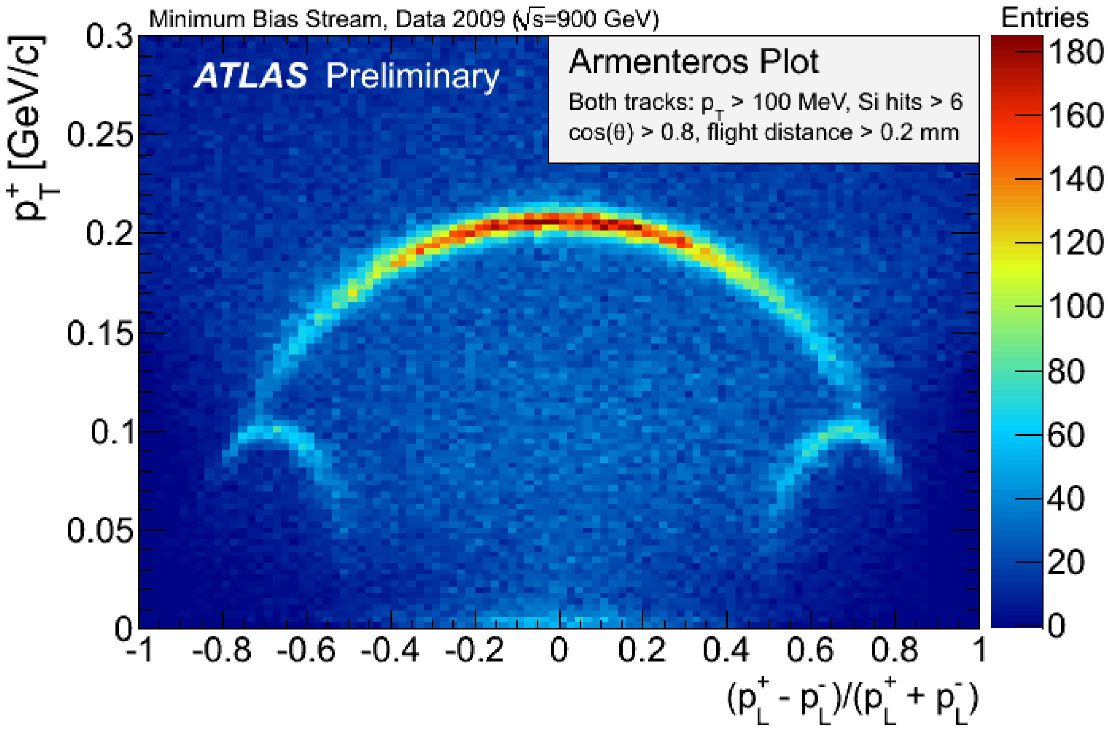


2009-12-06, 10:24 CET
Run 141749, Event 460665

Event with $K_S \rightarrow \pi^+\pi^-$ Candidate

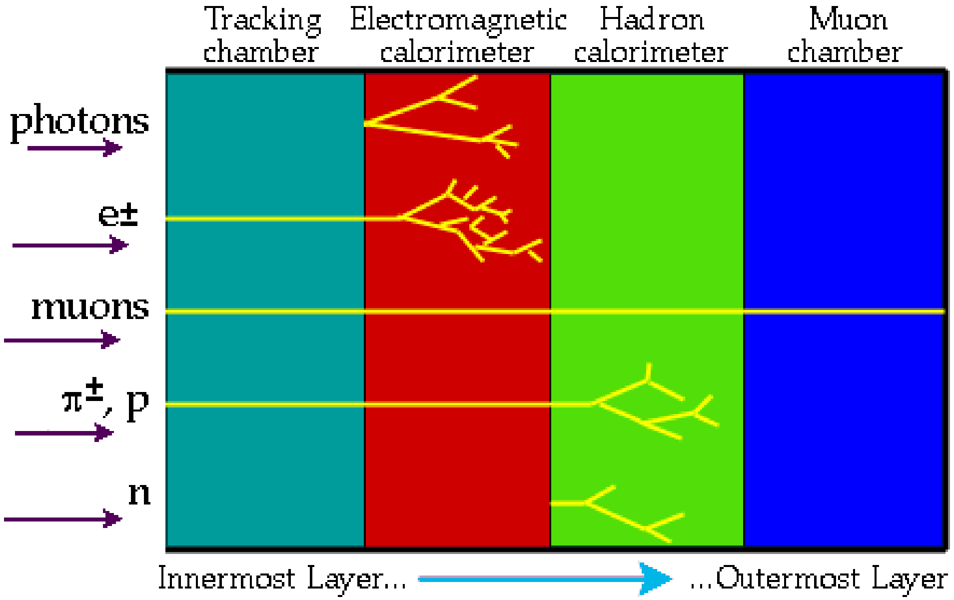
V^0 reconstruction

- ✓ **V^0s** can be reconstructed from the kinematics of their positively and negatively charged decay products, without needing to identify the π or p



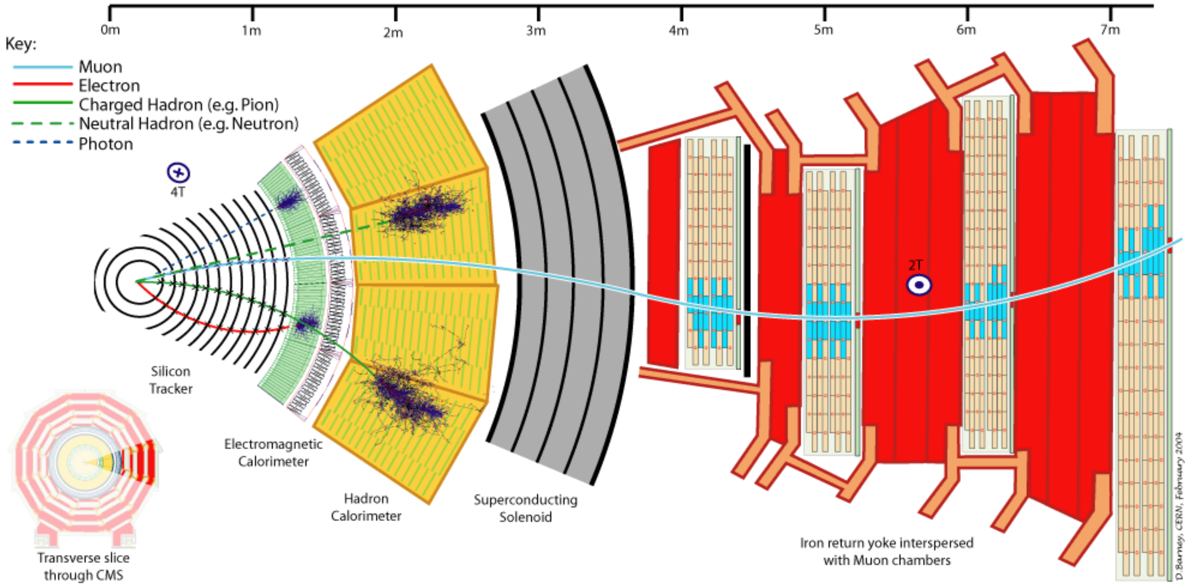
Other neutral hadrons

- ✓ **K_L^0 and neutrons** are detected in the hadronic calorimeter
  They feel the strong force, and when incident at high energy onto matter they produce showers of other hadrons
- ✓ Relevant scale is the nuclear interaction length **λ_I = 16.8 cm for Fe $\approx 10 \times X_0$**
  so hadronic showers are longer than EM → HCAL sits behind ECAL



General purpose detectors

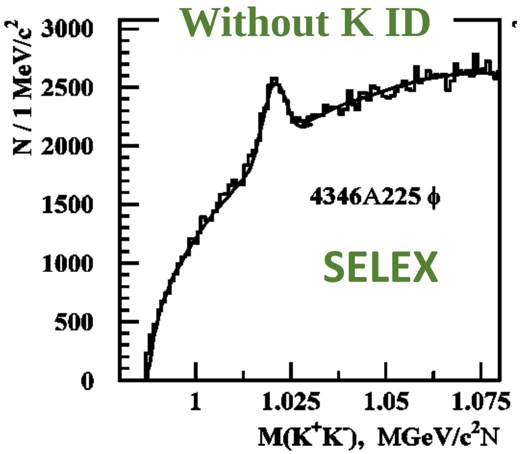
- ✓ Have now discussed the set of detectors used for particle identification in a typical General Purpose HEP experiment, such as **ATLAS** and **CMS**

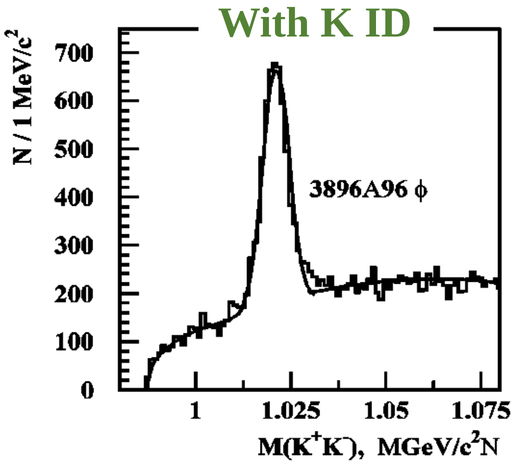


- ✓ One task that such General Purpose detectors do not do very well is to identify different charged hadrons **(π, K, p)**

Charged hadron ID

- ✓ Charged hadrons **(π, K, p)** are all effectively stable, and have similar interactions
  → track + hadronic shower
- ✓ However, identifying them can be crucial, in particular for the study of hadronic decays
- ✓ Example: the hadronic decay **$\phi \rightarrow K^+ K^-$**
- ✓ If we just make all two-track combinations in an event and calculate their invariant mass
  → large combinatoric background
  (most tracks are pions, from other sources)
- ✓ By identifying the two tracks as kaons, signal to background ratio is much improved



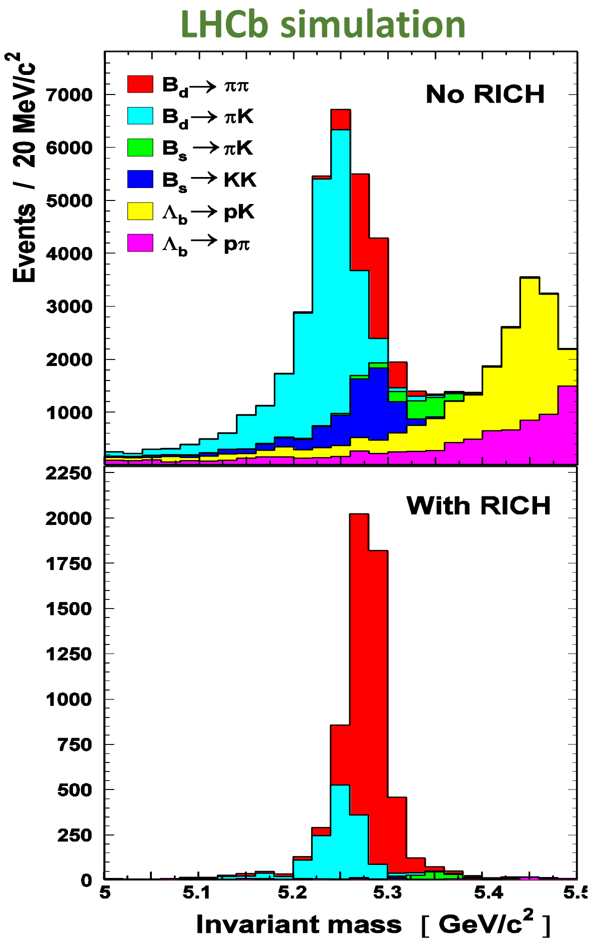


B physics

- ✓ Another example where hadron ID is crucial is in B physics: the study of hadrons containing the b quark
- ✓ B physics can shed light on the reason the Universe did not disappear soon after the Big Bang, from the annihilation of the matter and antimatter: CP violation can give rise to an excess of matter

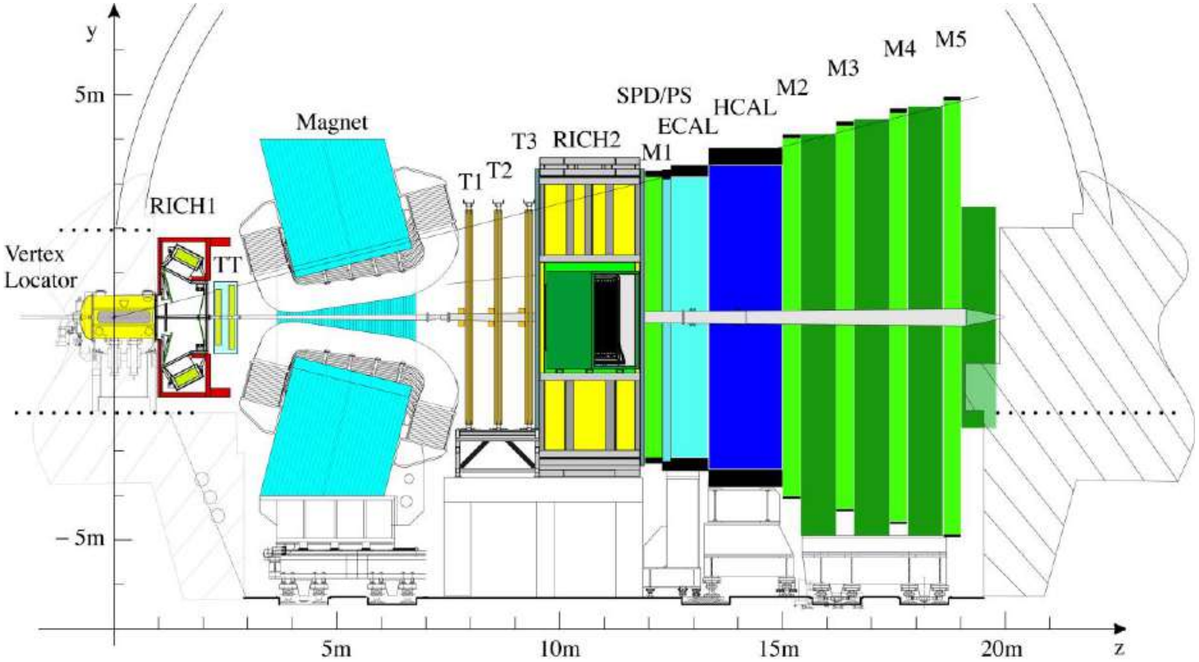
eg: $B(B^0 \to K^+ \pi^-) > B(B^0 \to K^- \pi^+)$

- ✓ If one makes combinations of all two-body B decays many different modes overlap → very difficult to study their properties
- ✓ Applying hadron ID, the different components can be separately studied



Dedicated detector

- ✓ LHCb is a dedicated detector for B physics at the LHC
- ✓ Since B hadrons are light ~ 5 GeV << E_{cm} (14 TeV) they tend to be produced in the forward direction, so LHCb is a forward spectrometer:



✓Otherwise it looks like a slice out of a General Purpose experiment, apart from two extra detectors – for identifying charged hadrons

QUIZZ

- ✓ How to identify quarks and gluons
- ✓ Give examples of "stable" and unstable hadrons from the point of view of a particle detector
- ✓ Give examples of neutral hadrons
- ✓ Identify Λ and K^0_S at slide 22

Methods

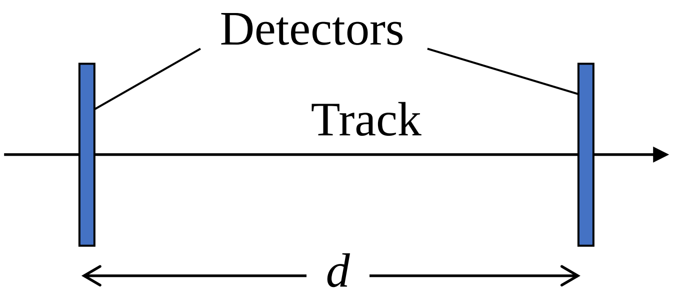
- ✓ Since the interactions of charged hadrons are similar, the most direct way to distinguish them is to determine their (rest) mass
- ✓ Their momentum is measured by the tracking system, so this is equivalent to determining their velocity, since $p = \gamma m v$, so $m = p/\gamma v = p/\gamma\beta c$
  There are four main processes that depend on the velocity of a particle that will be discussed in turn:
  1. Most direct is to measure the **Time Of Flight (TOF)** of the particles over a fixed distance
  2. Alternatively one can look at the detail of their interaction with matter
     The main source of energy loss is via **Ionization (dE/dx)**
  3. If the velocity of the particle changes compared to the local speed of light it will radiate photons, detected as **Transition radiation**
  4. If a particle travels at greater than the local speed of light, it will radiate **Cherenkov radiation**

Time Of Flight

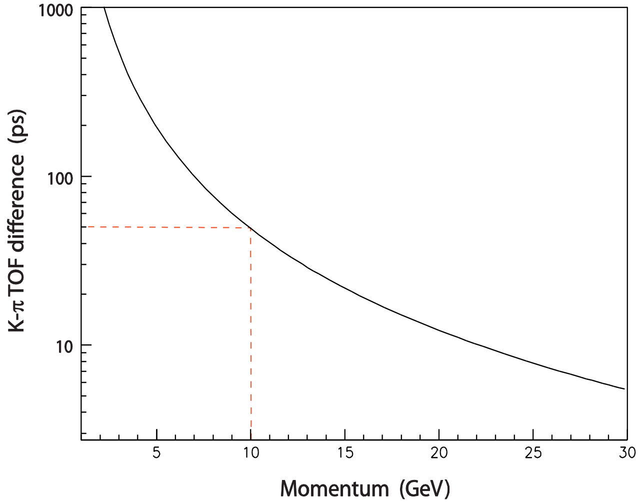
- ✓ Simple concept: measure the time difference between two detector planes

  $$\beta = d / c \, \Delta t$$

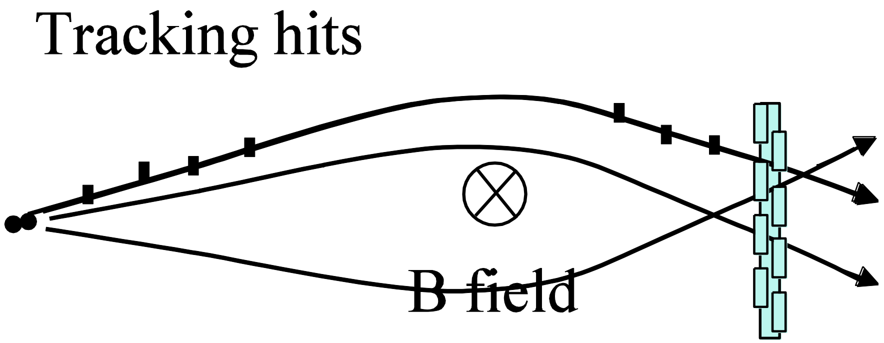
- ✓ At high energy, particle speeds are relativistic, closely approaching to c
- ✓ For a 10 GeV K, the time to travel 12 m is 40.05 ns, whereas for a π it would be 40.00 ns, so the difference is only 50 ps
- ✓ Modern detectors + readout electronics have resolution **σ_t ~ 10 ns**, fast enough for the LHC (bunch crossings 25 ns apart) but need **σ_t < 1 ns** to do useful TOF
- ✓ TOF gives good ID at low momentum Very precise timing required for p > 5 GeV



TOF difference for *d* = 12 m



Time Of Flight



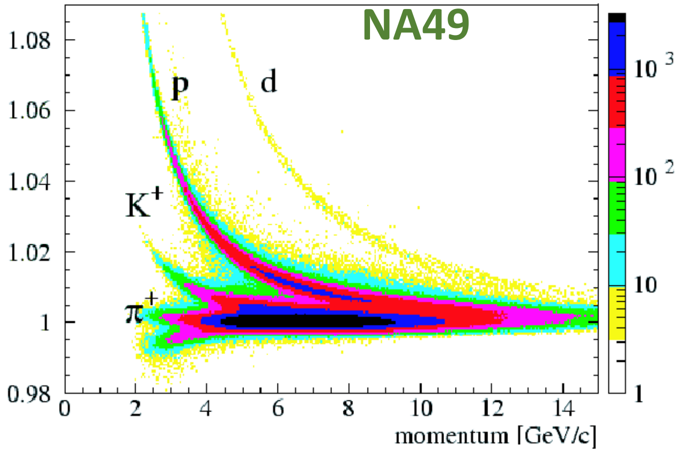
- ✓ Recall simple concept, measuring time difference between two detectors
- ✓ Can simplify by using time of beam crossing to provide the “start” signal
- ✓ Due to magnetic field, tracks are not straight lines
  → need to use tracking to determine actual path length
- ✓ Multiple tracks would give rise to ambiguous solutions
  → detector is segmented according to the expected track multiplicity
- ✓ This is the basic layout for TOF hodoscopes made of scintillator bars

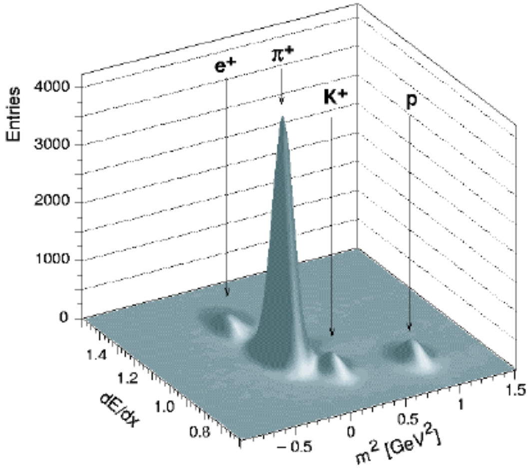
TOF Performance

- ✓ The number of standard deviations separation for a time of flight detector is

$$N_\sigma = \frac{|m_1^2 - m_2^2|\, d}{2\, p^2\, \sigma_t\, c} \qquad \textbf{(TOF)}$$

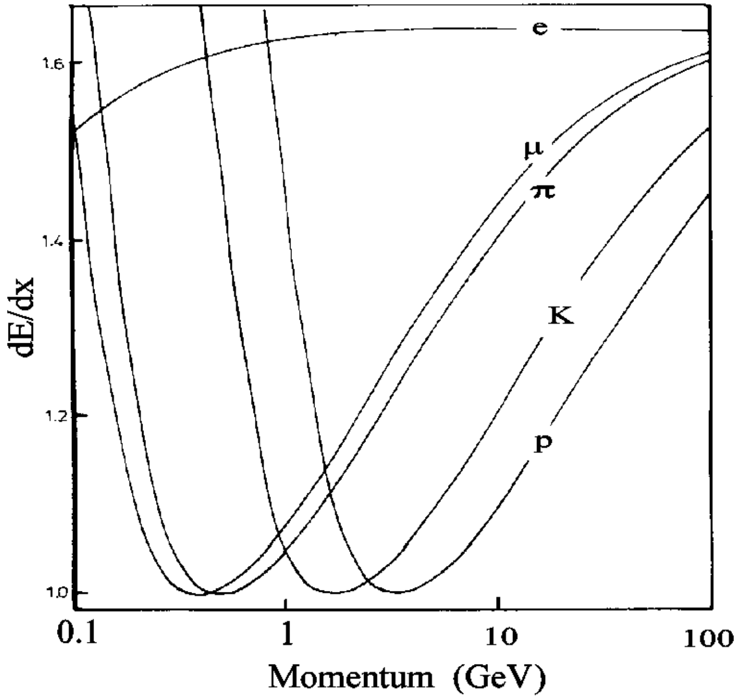
- ✓ Combination of TOF with dE/dx can help to remove ambiguities:





Ionization

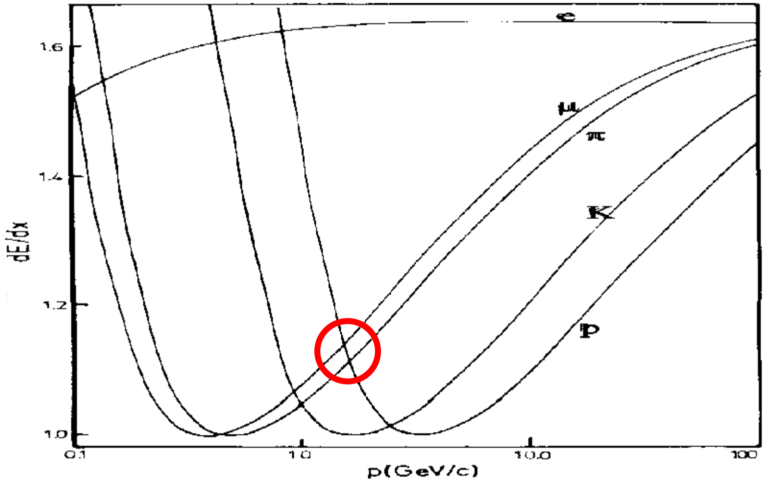
- ✓ Charged particles passing through matter can knock out electrons from atoms of the medium: ionization
- ✓ Energy loss described by the Bethe-Bloch formula, which gives the universal velocity dependence: **$dE/dx \propto \log(\beta^2\gamma^2) / \beta^2$**
- ✓ This can be used to identify particles, particularly at low momentum where dE/dx varies rapidly
- ✓ Advantage: uses existing detectors needed for tracking (but requires the accurate measurement of the charge)

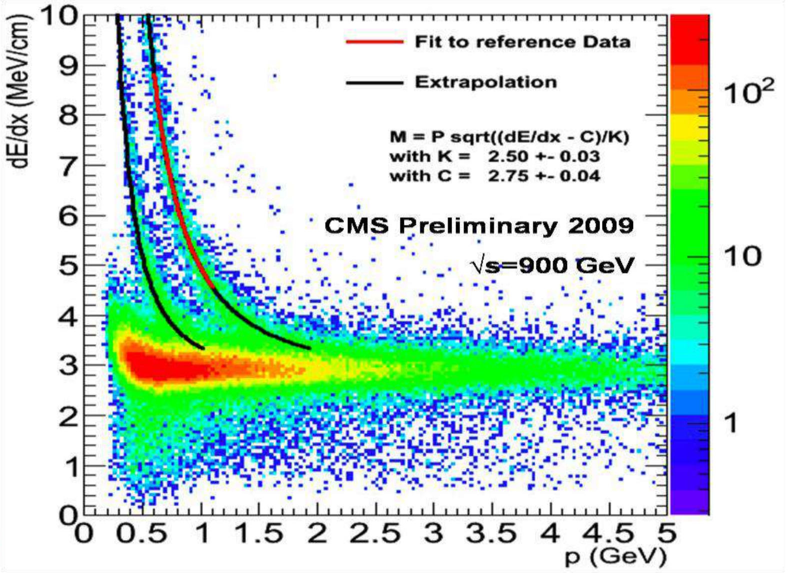


- ✓ **Note: these techniques all provide signals for charged leptons e, μ as well as π, K, p**
  But $m_\mu \approx m_\pi$, so they are not well separate (dedicated detectors do a better job)

dE/dx performance

- ✓ Note that the dE/dx plot as a function of momentum has a lot of overlap regions between the different mass hypotheses
  → limits usefulness for those momenta
- ✓ Good separation for low momentum
  Combine with other detectors to cover full momentum range





Transition Radiation

✓ Local speed of light in a medium with refractive index **n** is **$c_p = c/n$**

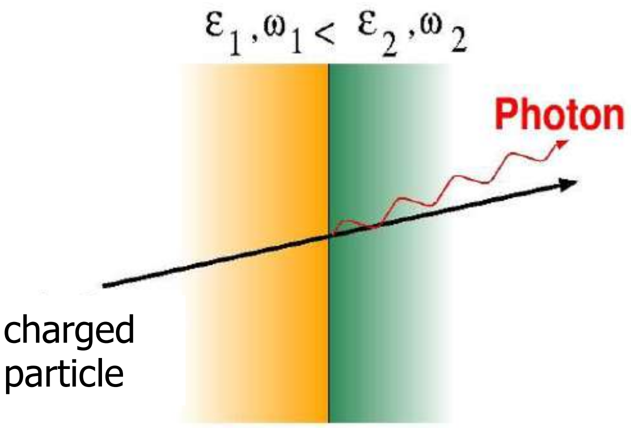
✓ If its relative velocity **v/c_p** changes, a particle will radiate photons:

1. Change of direction **v** (in magnetic field) → **Synchrotron radiation**
2. Change of **|v|** (passing through matter) → **Bremsstrahlung radiation**
3. Change of refractive index **n** of medium → **Transition radiation**

✓ Transition radiation is emitted whenever a relativistic charged particle traverses the border between two media with different dielectric constants **($n \sim \sqrt{\varepsilon}$)**

✓ The energy emitted is proportional to the boost γ of the particle

→ Particularly useful for electron ID
Can also be used for hadrons at high energy



Transition Radiation

- ✓ The Transition radiation energy emitted when charged particle crosses a boundary between vacuum and a medium with plasma frequency ω_p

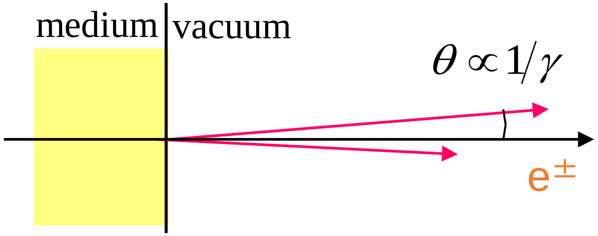
  $\Delta E = \alpha\, h\omega_p \gamma / 3$, where α = **fine structure constant ≈ 1/137**

- ✓ $h\omega_p$ depends on the electron density in the material
  ~ 20 eV for a low-Z material such as plastic (eg polypropylene)

  For a **10 GeV** electron, **$\gamma \sim 2 \times 10^4$, so $\Delta E \sim$ keV (X-ray energy)**

- ✓ Low probability of photon emission at one interface (~ 1%)
  so many layers of thin foils are used for the radiator
  Low Z is important to limit re-absorbtion of the radiation

- ✓ Radiation emitted in the very forward direction,
  in cone of angle $1/\gamma$ around the particle direction
  → photons will be seen in same detector as the ionization from the track



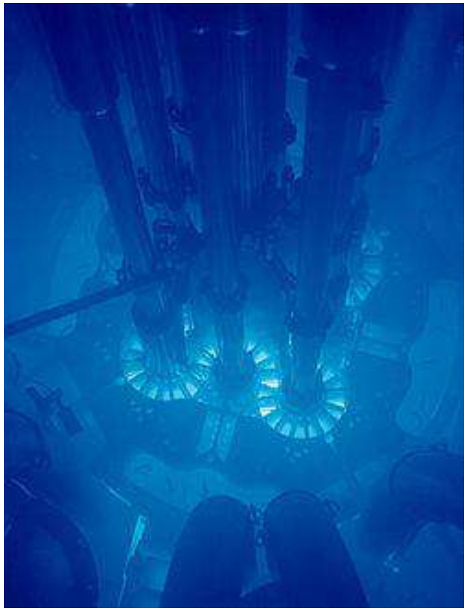
Cherenkov Radiation

- ✓ Cherenkov light, emitted with **$\cos\theta_C = 1/\beta n$**, is produced equally distributed over photon energies, which when transformed to a wavelength distribution implies it is peaks at low wavelengths – it is responsible for the blue light seen in nuclear reactors
- ✓ The number of photons detected in a device is:

$$N_{pe} = \frac{\alpha^2 L}{r_e m_e c^2} \int \varepsilon \sin^2\theta_C \, dE, \text{ where } \frac{\alpha^2}{r_e m_e c^2} = 370\ \mathrm{cm}^{-1}\mathrm{eV}^{-1}$$

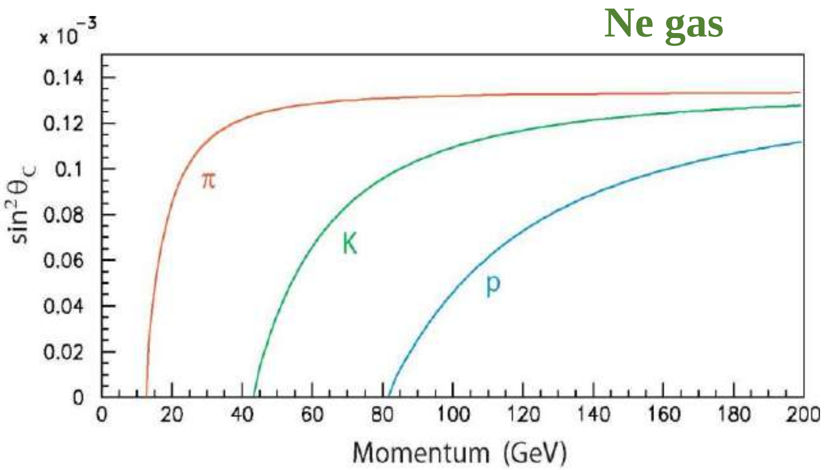
L is the length of the radiator medium
ε is the efficiency for detecting the photons

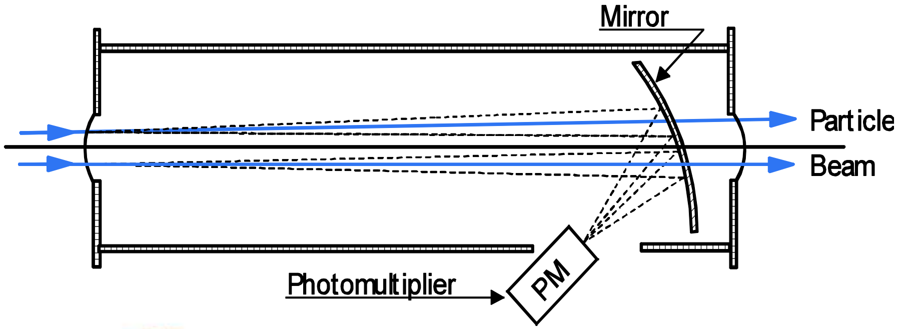
- ✓ There is a threshold for light production at $\beta = 1/n$
  - Tracks with $\beta < 1/n$ give no light
  - Tracks with $\beta > 1/n$ give light

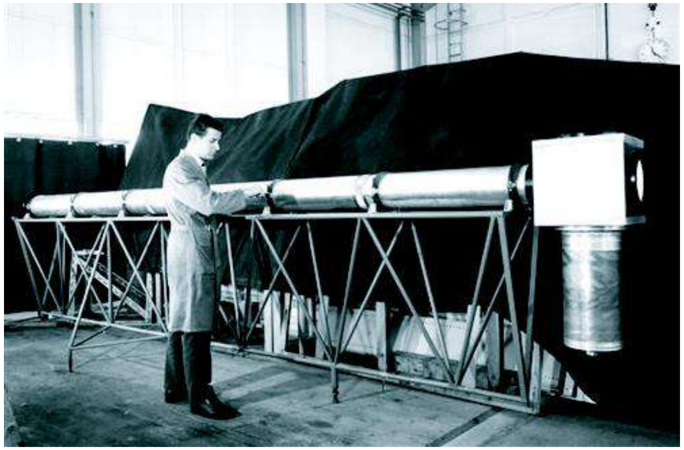


Threshold detectors

- ✓ This is the principle of "threshold Cherenkov detectors" which are useful to identify particles in a beam line (with fixed momentum)
  for example a 50 GeV π^+ beam with some proton contamination
- ✓ By choosing a medium with a suitable refractive index, it can be arranged that the π will produce light, but the protons will not

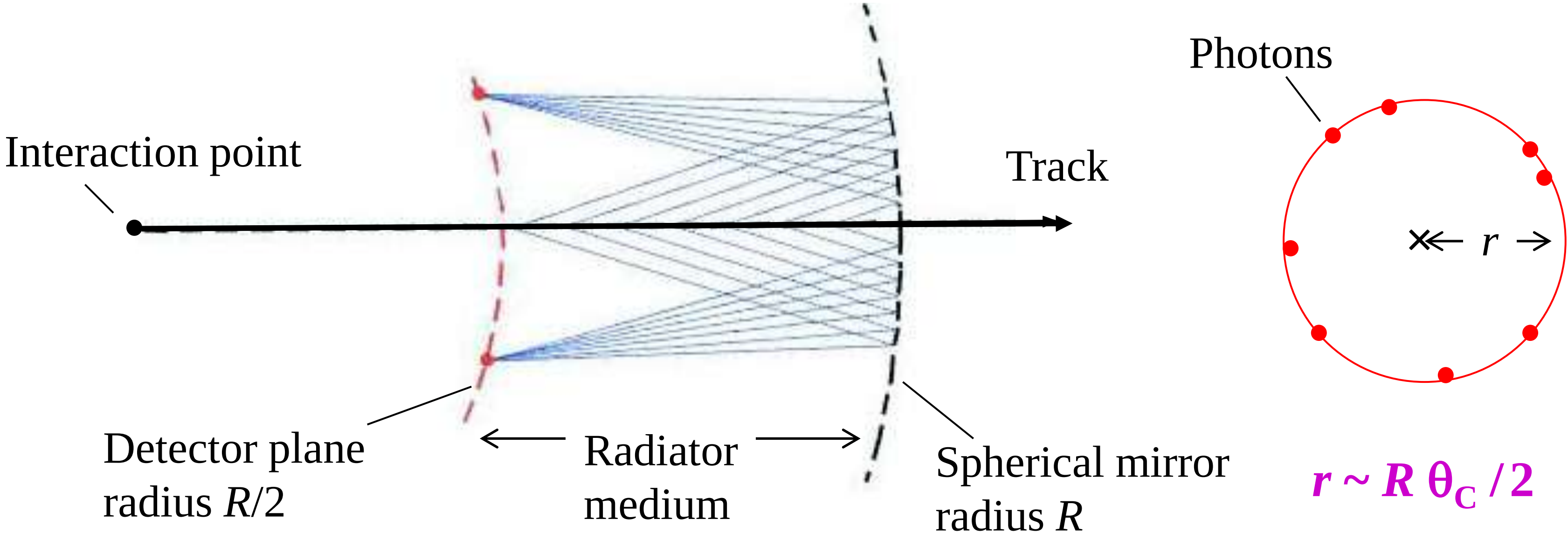






Ring Imaging

- ✓ Threshold counters just give a yes/no answer, and are less useful when the tracks have a wide momentum range. However, more information can be extracted from the Cherenkov angle
- ✓ The Cherenkov cone can be imaged into a ring, using a spherical mirror. Measuring the ring radius allows Cherenkov angle to be determined



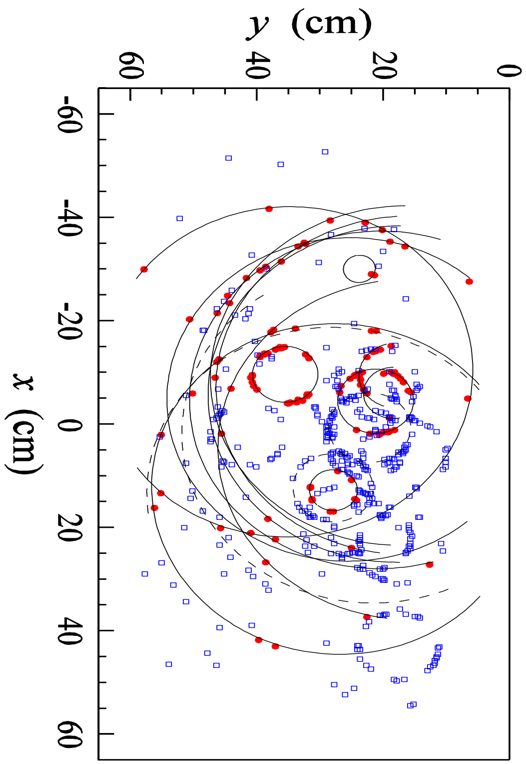
$r \sim R\,\theta_C\,/\,2$

Pattern recognition

- ✓ In the busy environment of hadronic collisions (such as at the LHC) many tracks may pass through the detector
  → overlapping rings
- ✓ Deciding which hit belongs to which track requires pattern recognition
- ✓ Most approaches rely on the use of the track to seed the ring search:
  after transformation through the optics of the RICH, the track image will lie at the centre of the ring
- ✓ The ring search then corresponds to the search for a peak in the number of photon hits versus radius from the track

Simulated event in RICH-1 / LHCb

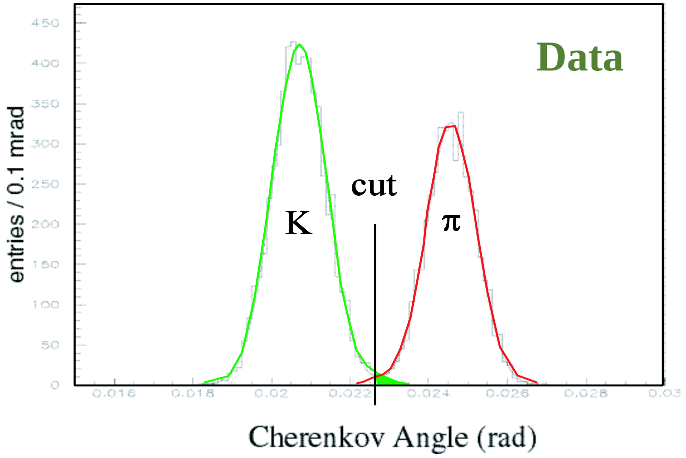
Large rings: aerogel, small: C_4F_{10}

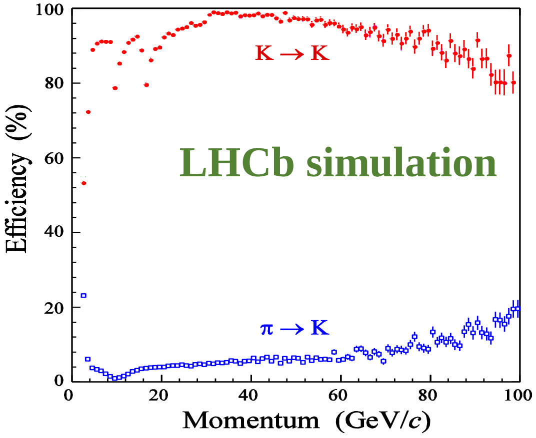


Particle separation

- ✓ Separating two particle types using the signal from a RICH detector is illustrated for K and π from a test beam
- ✓ ~ Gaussian response, σ_θ ~ 0.7 mrad
  Peaks are separated by 4 mrad = 6 σ_θ

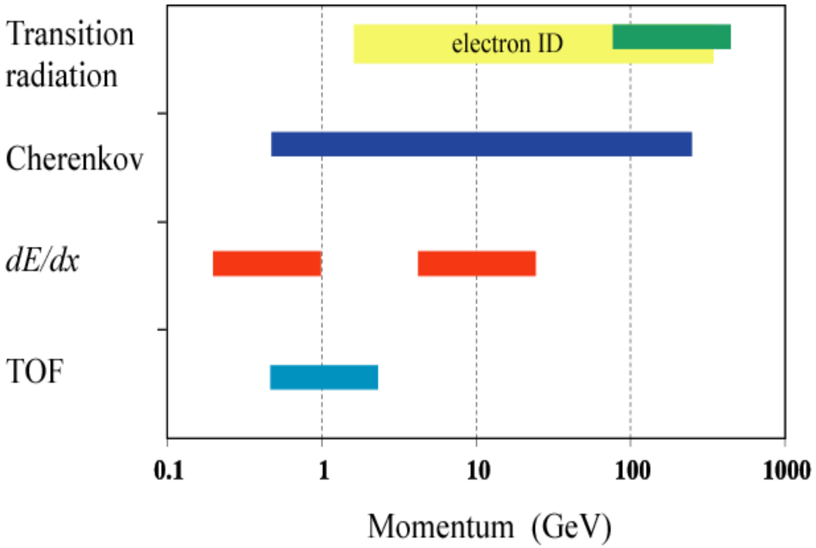
  Generally: $N_\sigma = \dfrac{|m_1^2 - m_2^2|}{2\,p^2\,\sigma_\theta\,\sqrt{n^2-1}}$
- ✓ *Note the similarity to the expression for TOF, but the amplification factor* $1/\sqrt{n^2-1}$ *is missing in that case → TOF identification works at lower momenta.*
- ✓ Adjusting the position of the cut placed between the two peaks to identify a ring as belonging to a K or π gives a trade-off between efficiency and misidentification
- ✓ Studied in detail for the LHCb RICH system using Monte Carlo simulation





Identification of charged hadrons

- ✓ There is a wide variety of techniques for identifying charged particles
- ✓ **Transition radiation** is useful in particular for electron identification
- ✓ **Cherenkov** detectors are in widespread use. Very powerful, tuning the choice of radiator
- ✓ **Ionization** energy loss is provided by existing tracking detectors but usually gives limited separation, at low p
- ✓ **Time Of Flight** provides excellent performance at low momentum
  With the development of faster photon detectors, the range of TOF momentum coverage should increase



Summary

- ✓ Particle identification is a crucial aspect of most high energy physics experiments, in addition to tracking and calorimetry
- ✓ Short-lived particles are reconstructed from their decay products
- ✓ Most long-lived particles seen in the experiment can be identified from their signatures in the various different detectors
- ✓ Distinguishing the different long-lived charged hadrons (π, K, p) is more challenging, and usually requires dedicated detectors
- ✓ Their identification is based on four main processes: TOF, dE/dx, Transition radiation and the Cherenkov effect